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DC and AC High Dynamic Range pixels

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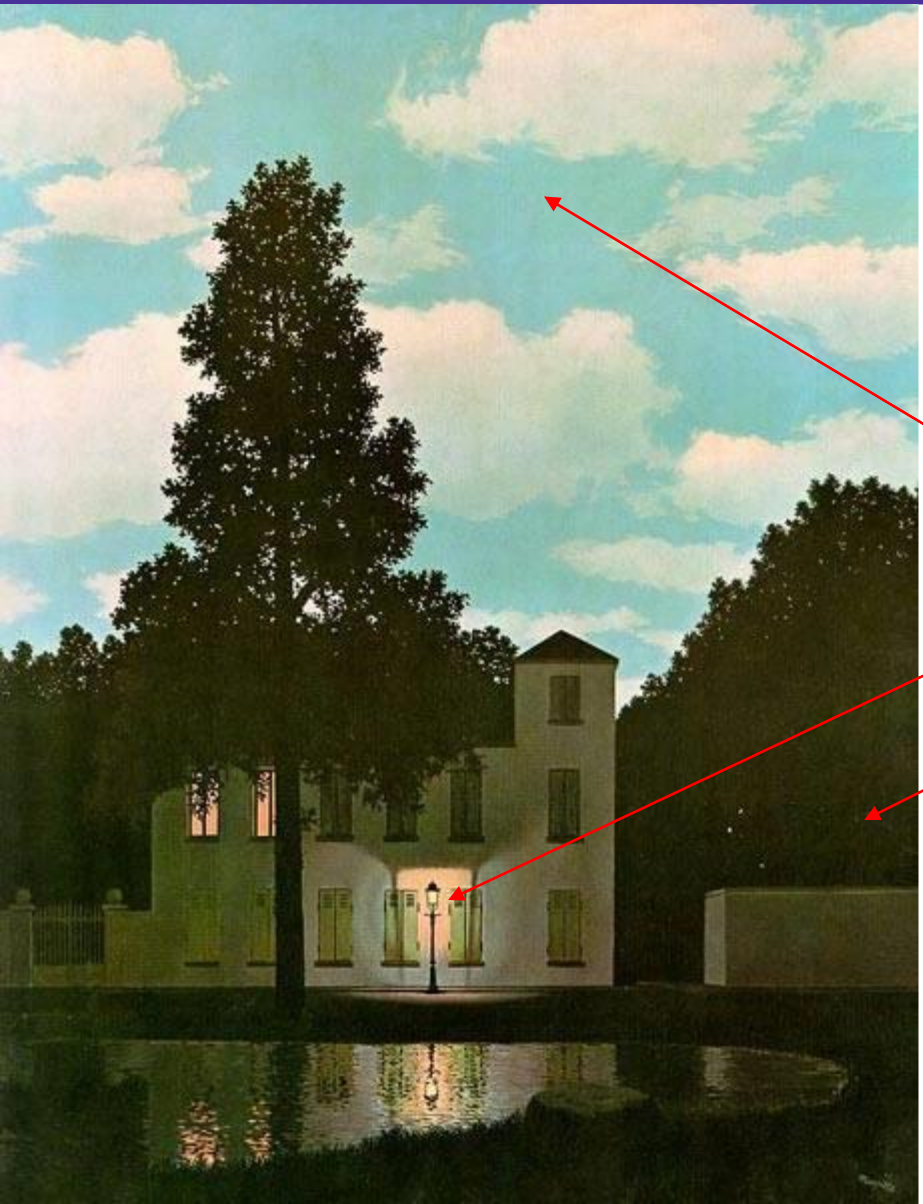
Contents

Outline

1. Why do we need a high dynamic range sensor?
2. Definitions of DR
3. Obtain a high DC dynamic range by non-linearity
4. AC high dynamic range pixel
5. Conclusions

A high dynamic range scene



René Magritte, “l’ Empire des lumières” 1954

Ceci n’est pas une “High dynamic range scene”

100000 lx

100 lx

< 1 lx

Highlight
partly overexposed

Capture the whole scene, and then try to recover detail and contrast over the full scene dynamic range

In the shadow of a
dark scene

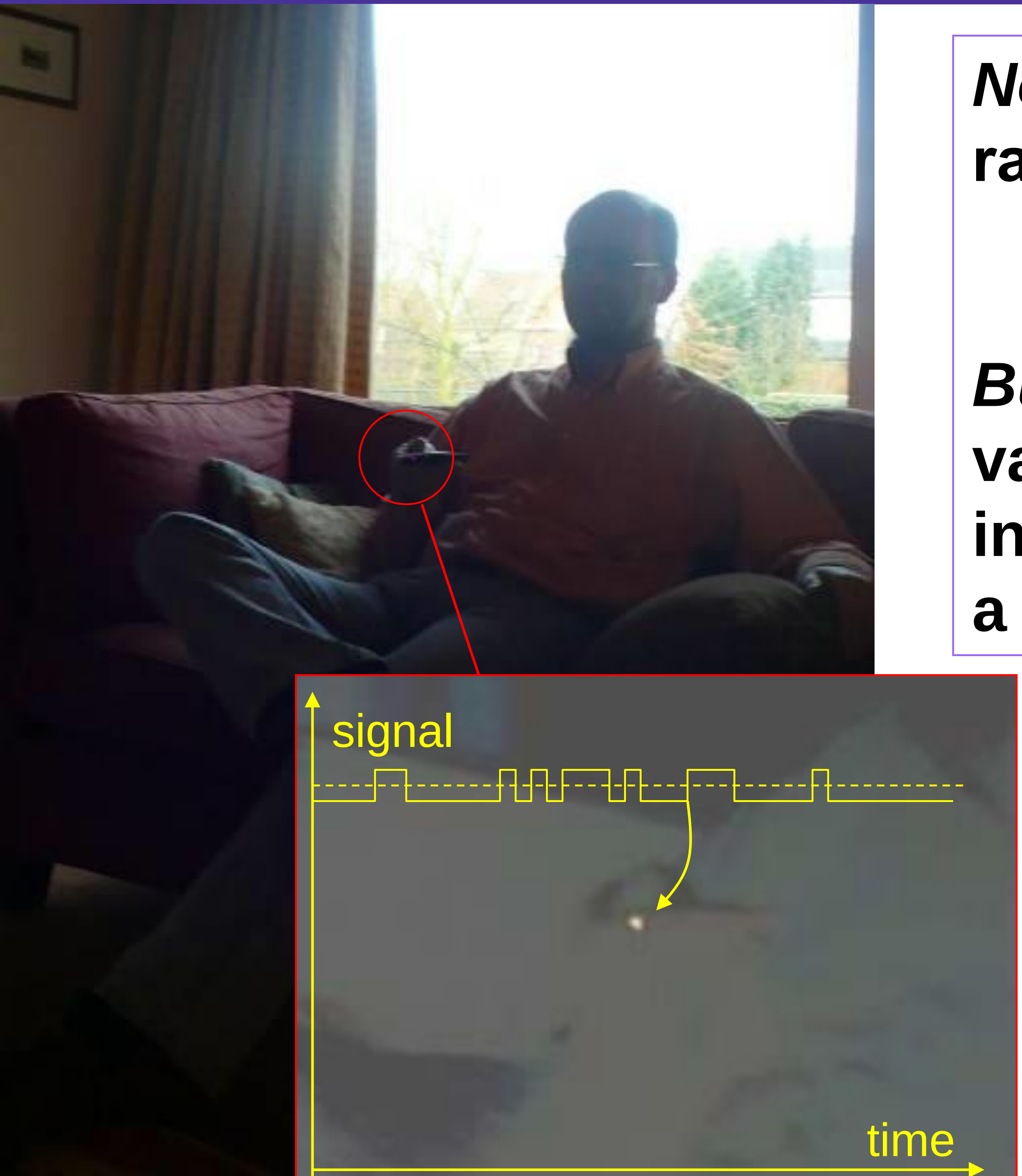
Why do we need a wide dynamic range sensor?

DC

- To catch highlights
- To allow us to be lazy and not adjust camera speed to the scene
- To discriminate objects in any part (dark/bright) of the scene / picture

→Catch the whole scene / range

AC high dynamic range



Not: **capture the whole range ("DC")**

But: **capture the time varying small signal of interest in the presence of a large DC background**

Why would we need a wide dynamic range sensor?

AC

- To extract *AC information only* from a scene
- To recover weak AC information buried in a large DC background
  - Narrow band: exchange noise ~ noise bandwidth
- For specific purposes
  - Distance ranging
    - time of flight method
  - Time gating
    - making the sensor sensitive during precise times spans
  - Patterned light; 3D imaging; …

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Dynamic Range definition?

DR$_{wikipedia}$

Wikipedia: "Dynamic range is a term used frequently in numerous fields to describe the ratio between the smallest and largest possible values of a changeable quantity, such as in sound and light."

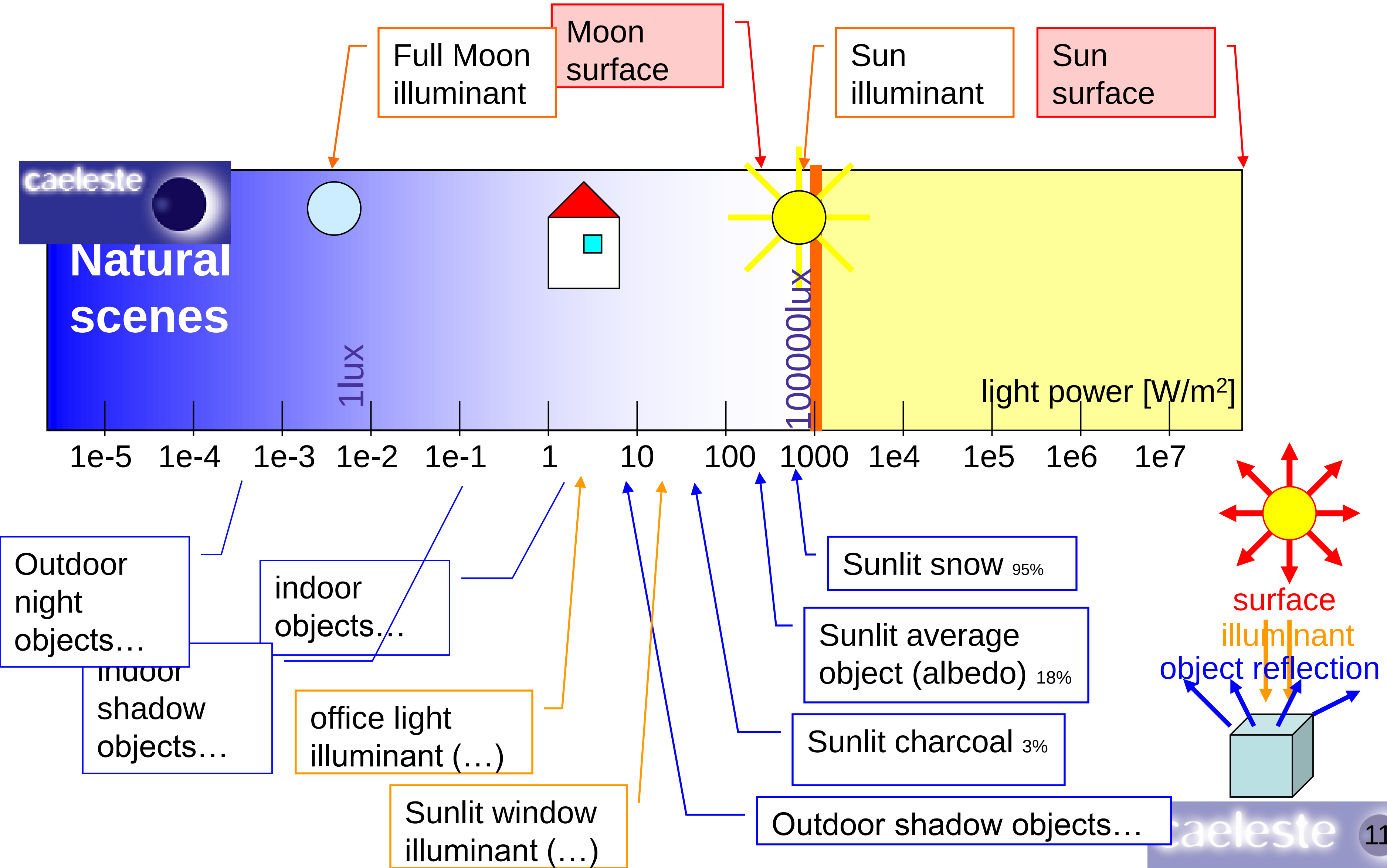
Applies to the scene, not to the sensor

- Our "changeable quantity" is "P", "light"
  [W, W/m2, photons, lux…]
- "signal", "S", is the measurement result
  [V, ADC bits…]

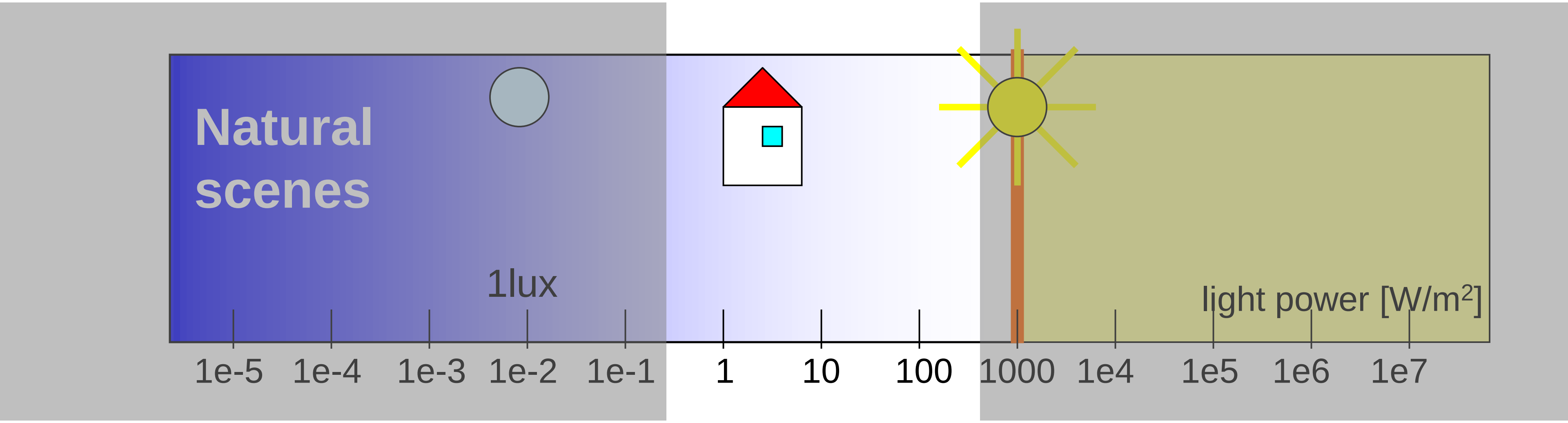
AC or DC

Natural scenes

may have a huge dynamic range



"linear" dynamic range definition



Linear response sensor:

S/N or SNR = Dynamic Range?

- typical: Between 1000: 1 = 60 dB — S_{max}≈1V, N≈1mV$_{RMS}$
- extreme high end: 10000:1 = 80 dB — S_{max}≈2V, N≈200μV$_{RMS}$

dynamic range definition no.1

"DR is in light power domain what S_{max}/N_{min} is in voltage (signal) domain"

Image sensor detection chain

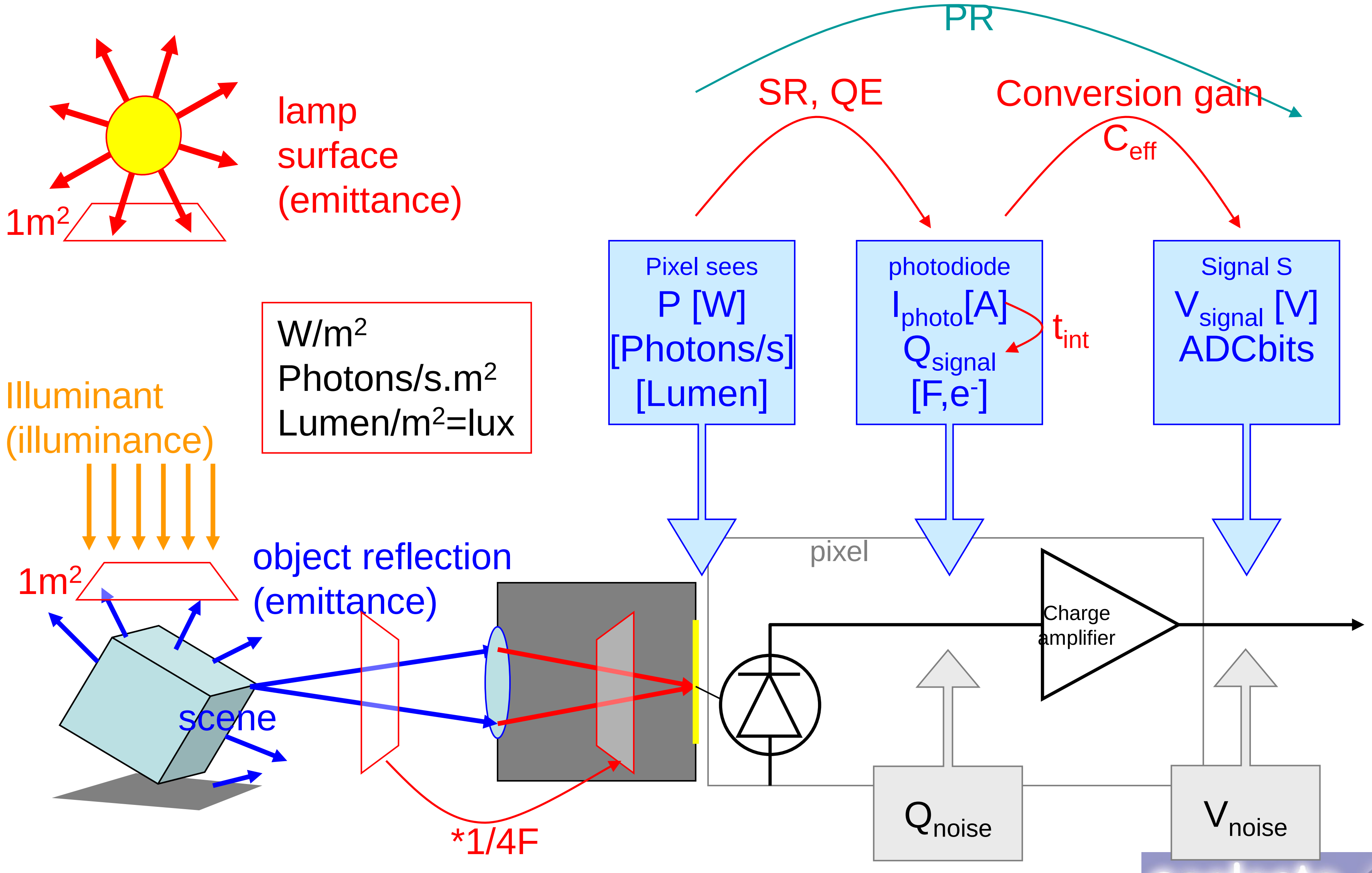
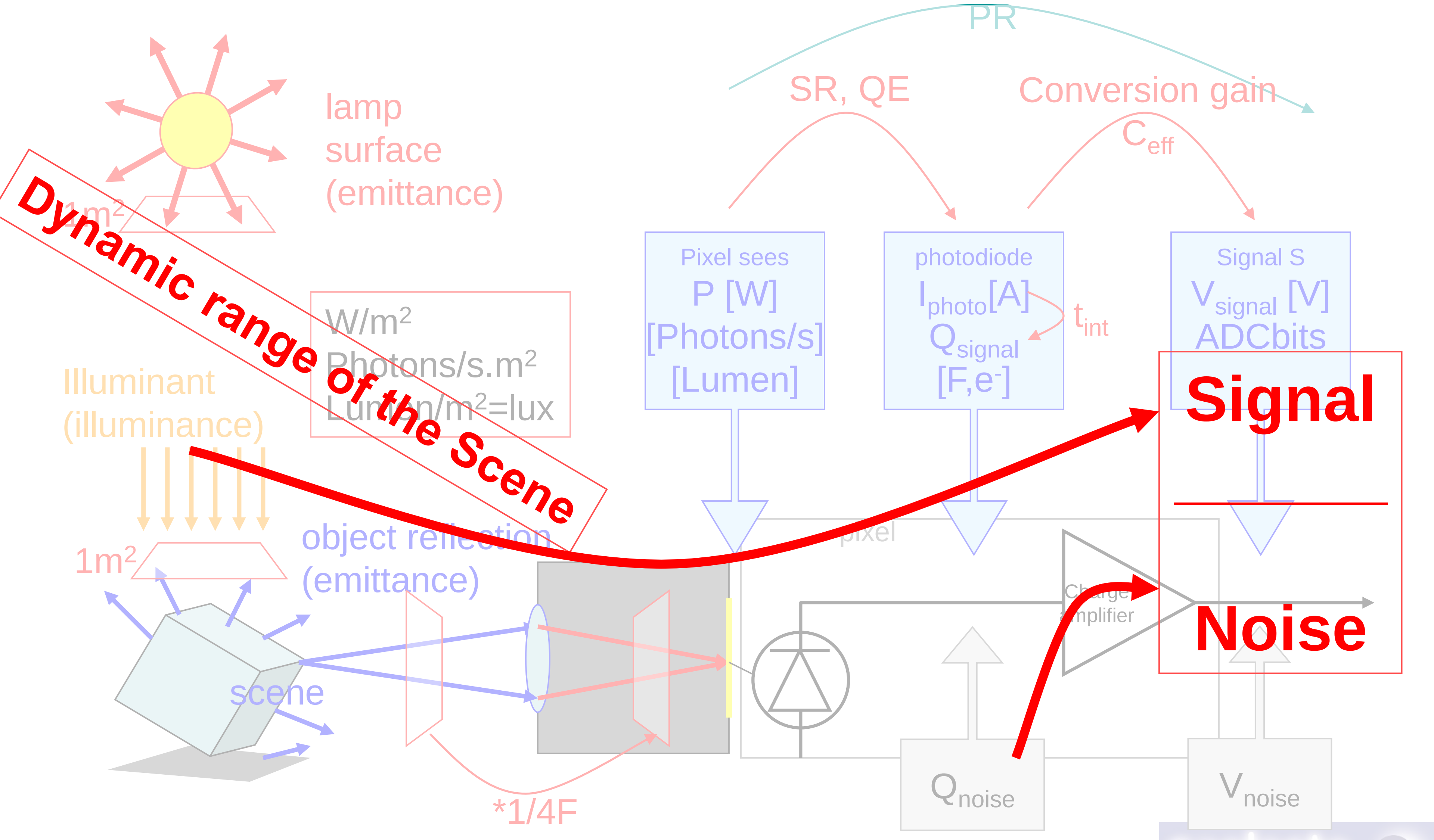
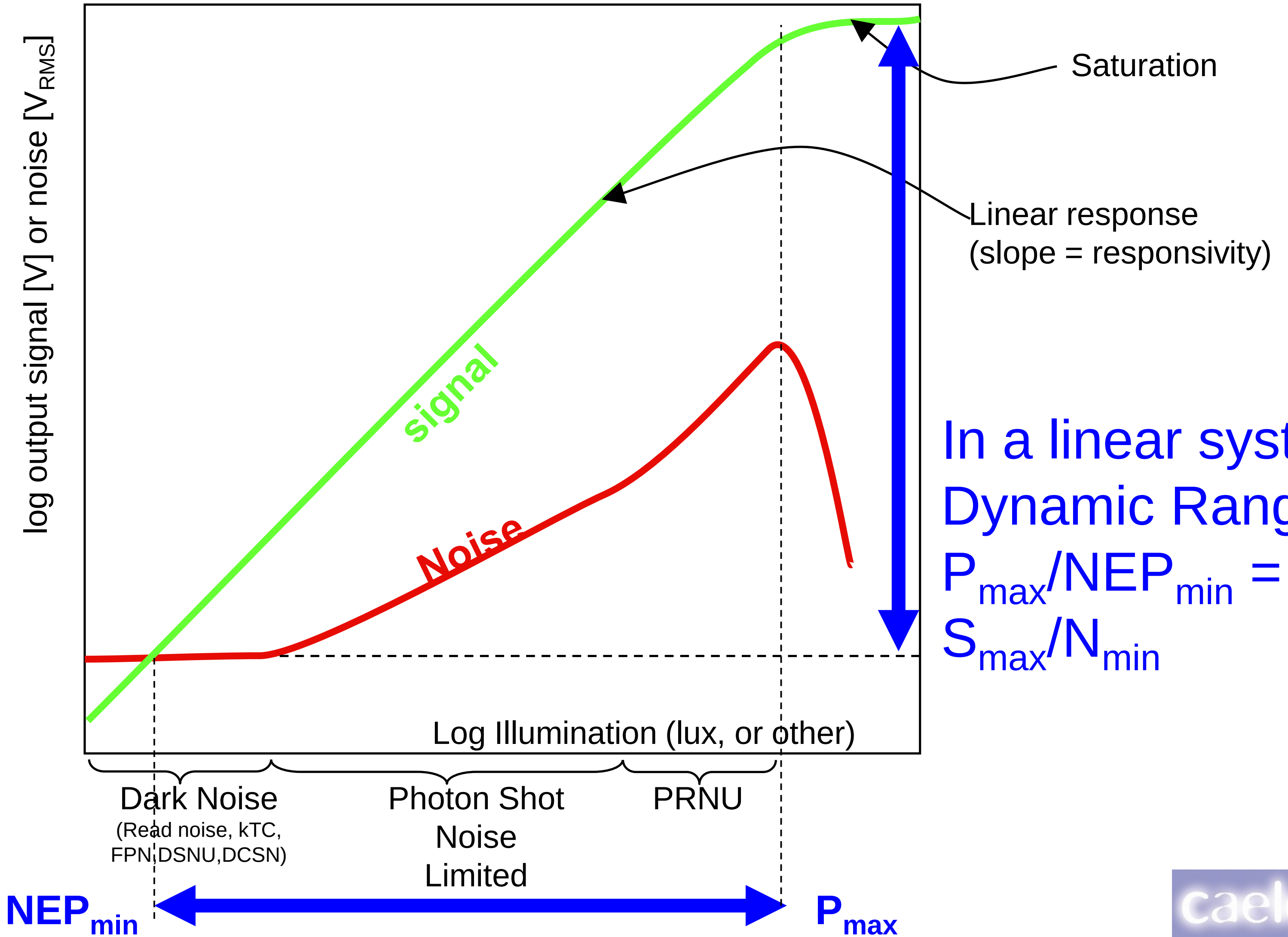


Image sensor detection chain



DR = S/N ?



In a linear system
Dynamic Range =
P_{max}/NEP_{min} =
S_{max}/N_{min}

How to push DR beyond S_{max}/N_{min}

In a linear, DC coupled, system, Dynamic Range is very closely related to Signal/Noise

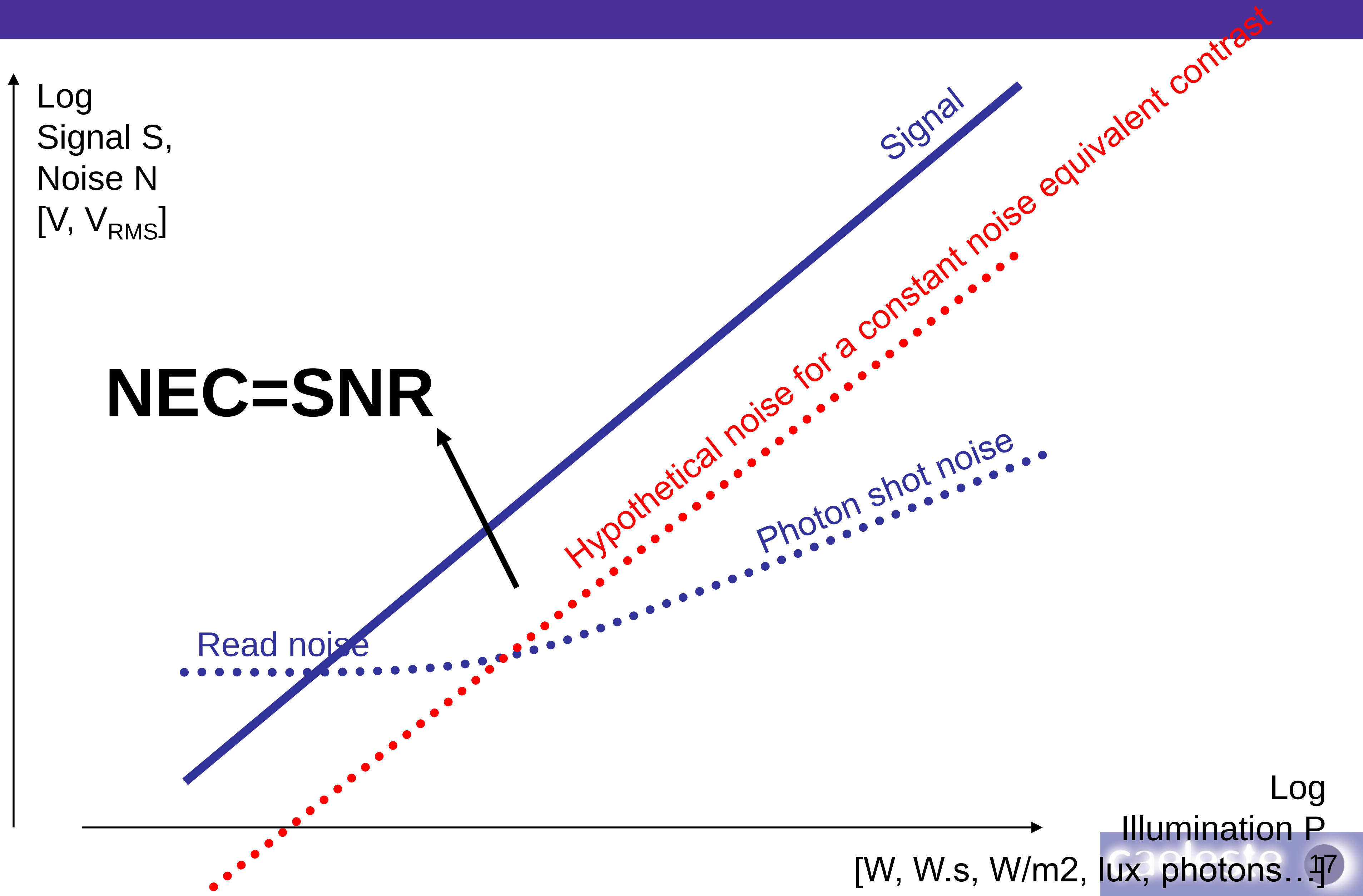
$$DR = \frac{P_{\max}}{NEP_{\min}} \approx \frac{V_{signal_{\max}}}{V_{noise_{\min}}} < ...10000:1$$

Ways out:

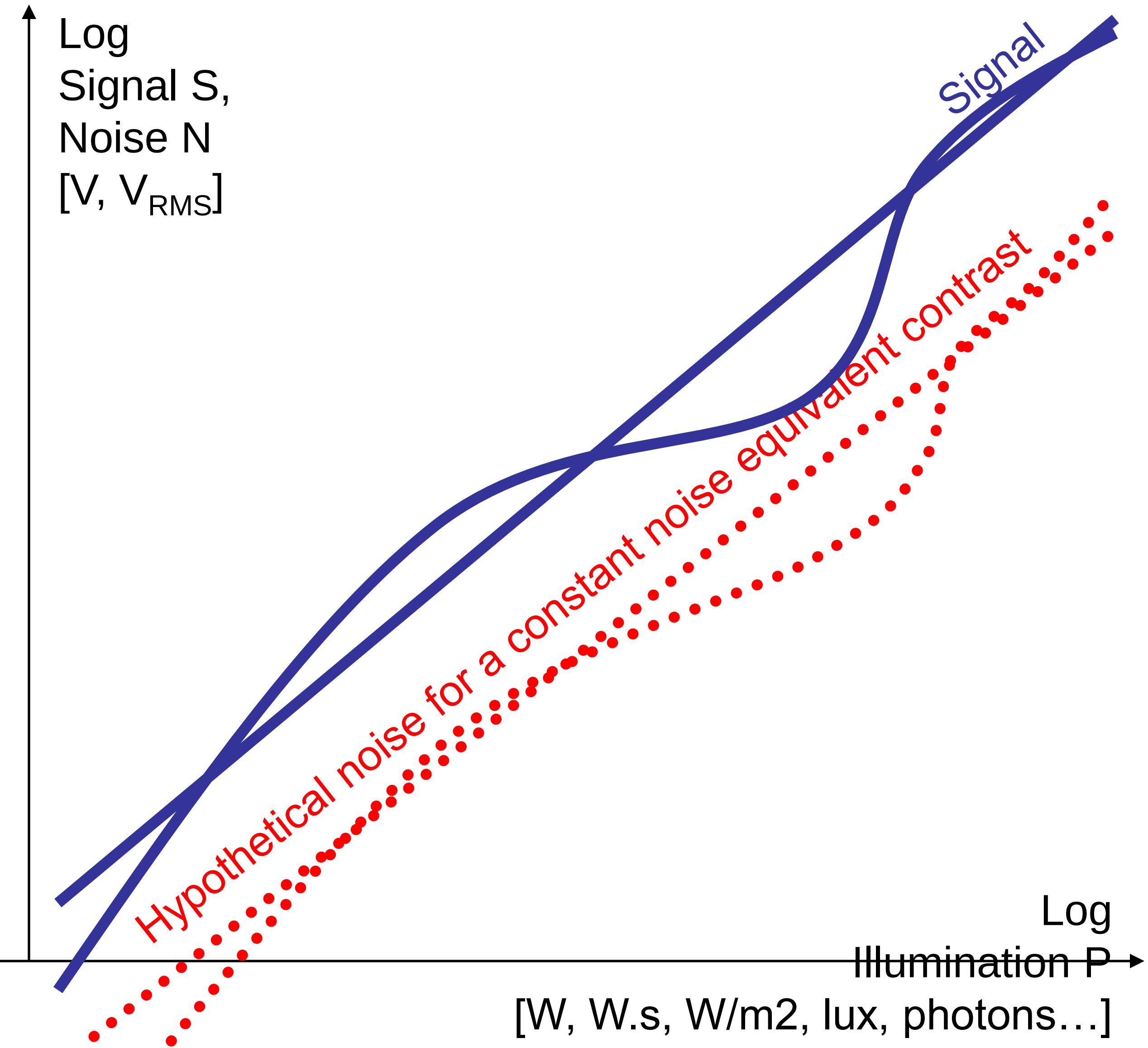
⇨**Non-linear response**

⇨**AC signal detection** ⇨**AC dynamic range**

Constant N.E.Contrast - linear



Noise Equivalent Contrast - general



$$NEC = \frac{P}{NEP}$$

$$NEP = \frac{N}{Photoresponse} = \frac{N}{\left(\frac{\partial S}{\partial P}\right)}$$

$$NEC = \frac{P}{NEP} = \frac{P \cdot \frac{\partial S}{\partial P}}{N}$$

DC Dynamic Range definitions

Further attempts for definition

You can vote

- The range of light intensity levels that can be captured by the image sensor within a single frame DR_{SNRmax}
- The range of illumination levels on a similar object within the same frame, for which the object is recognizable (=decent contrast, after image processing)
- The range of intensities that can be captured, for which the SNR has at least a certain value DR_{SNR10}
- The range of intensities that can be captured for which the Noise Equivalent Contrast (NEC) has at least a certain value DR_{NEC10}

Summary of definitions for [DC] dynamic range

definition	**Symbol**	**How to obtain**
Signal to Noise Ratio	S/N_{max} SNR_{max}	sensor signal voltage range / sensor signal noise in the dark
Differential or small-signal signal to noise ratio	dS/dN dSNR	signal voltage / signal noise at that same signal level
Noise equivalent contrast ratio	NEC	The ability to discriminate between nearby grey levels *=1/(dSNR)*PR (where PR=photo response)*
Dynamic range	DR_{max}	Saturation *intensity* divided by noise equivalent *intensity* in the dark In a linear system this is the same as SNR_{max}.
Generalized dynamic range	$DR_{SNR\mathit{1}}$	the ratio between upper and lower *intensities* for which dSNR≥[value]
Generalized dynamic range	$DR_{NEC\mathit{10}}$	the ratio between upper and lower *intensities* for which NEC ≥ [value]
Linear dynamic range	LDR_x	DR_x with largest intensity for which dVolt/dIntensity is linear
ADC (E)NOB		Number of (effective) bits in the sensor's digital output
bits		Number of bits after image processing

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Obtain high *DC* high dynamic range by non-linearity

non-linear response

- a way to increase the sensor's capability to capture a wide dynamic range scene

- a way to exploit the fact that the noise level depends on the scene contents

We do not need a high DR

We need a high NEC

Goals

1. make a pixel that can capture a high DC dynamic range – *means actually*
2. reach a constant or minimal NEC over the largest possible [dynamic range]$_{\text{wikipedia definition}}$

Assumptions

1. NEC is needed to allow recovery of details in all parts (dark, bright) of the scene
2. **Unproven underlying hypothesis: the largest range is obtained when NEC is just large enough, i.e. constant**

$$NEC = \frac{P}{NEP} = \frac{P \cdot \frac{\partial S}{\partial P}}{N} = \text{constant}$$

In search for a high DR

- Exercise of thought:
  - Obtain the constant NEC by exploiting non-linear response
    - Increase DR by sacrificing NEC where it is sufficient
  - Non-linear response is obtained by
    - A non-linear transconductance, gain or $C_{effective}$
    - A non-linear integration time t_{int}

$$V_{signal} = \frac{t_{\text{int}} \cdot I_{photo}}{C_{eff}}$$

$$V_{signal} = \frac{t_{int} \bullet I_{photo}}{C_{eff}}$$

$$V_{signal} = \frac{Q_{signal}}{C_{eff}}$$

$$V_{noise} = \frac{Q_{noise}}{C_{eff}}$$

Modulation of the integration time

•Multiple slope response (piece-wise linear slopes)

•Non Destructive Readout

Modulation of the time constant

•Logarithmic response

•Lin-log

Modulation of the integration capacitance

•CCD with two wells

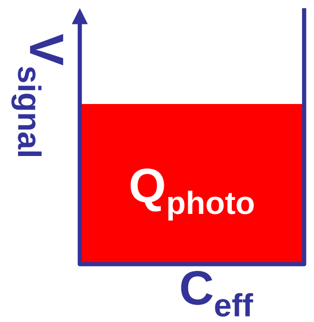
•Overflow MOSFET capacitors

•Adding multiple shorter integration periods

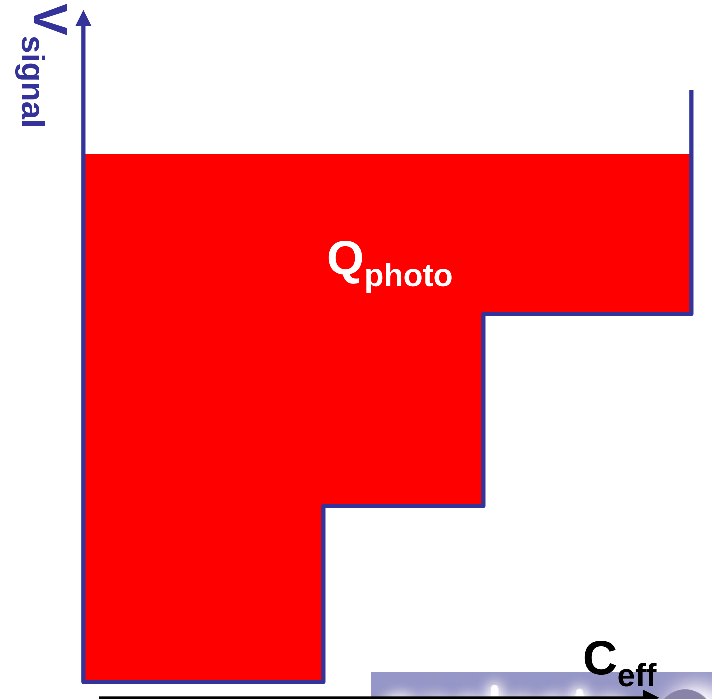
•Smart reset pixels

Non-linear $V_{signal}(Q)$

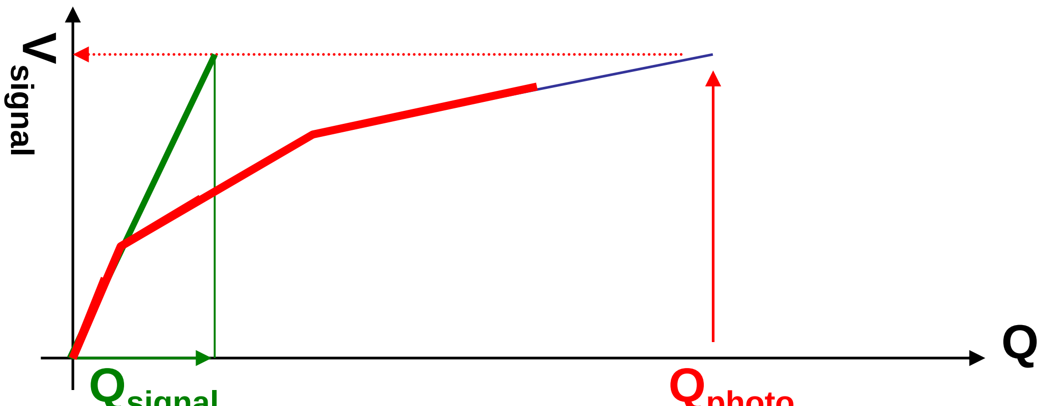
$$V_{signal} = \frac{t_{\text{int}} \cdot I_{photo}}{C_{eff}} \quad \text{(linear)}$$



$$V_{signal} = \sum \frac{t_{\text{int}} \cdot I_{photo}}{C_{eff}} = \frac{Q_{photo}}{t_{\text{int max}}} \cdot \sum \frac{t_{\text{int}}(Q)}{C_{eff}(Q)}$$



slope = $t_{int}(Q)/C_{eff}(Q)$



NEC as function of $V_{signal}(Q)$

$$NEC = \frac{P}{NEP} = \frac{P \cdot \frac{\partial S}{\partial P}}{N}$$

$$S = V_{signal} = \sum \frac{t_{\text{int}} \cdot I_{photo}}{C_{eff}} = \sum \frac{t_{\text{int}} \cdot P \cdot SR}{C_{eff}}$$

$$V_{signal} = S$$

$$V_{noise} = N$$

SR=Spectral Response [A/W]

$$\frac{\partial S}{\partial P} = \sum SR \cdot \left(\frac{t_{\text{int}}}{C_{eff}} + \frac{\frac{\partial t_{\text{int}}}{\partial P} \cdot P}{C_{eff}} - \frac{t_{\text{int}} \cdot P \cdot \frac{\partial C_{eff}}{\partial P}}{C_{eff}^{\ 2}} \right)$$

When one lets integration time depend on P or Q_{photo}

$$NEC = \frac{P}{N} \cdot \frac{\partial S}{\partial P} = \frac{SR \cdot \left(\frac{t_{\text{int}} \cdot P}{C_{eff}} + \frac{\frac{\partial t_{\text{int}}}{\partial P} \cdot P^2}{C_{eff}} - \frac{t_{\text{int}} \cdot P^2 \cdot \frac{\partial C_{eff}}{\partial P}}{C_{eff}^{\ 2}} \right)}{N}$$

When one lets C_{eff} depend on P or Q_{photo}

caeleste

NEC = constant, excercise

- Postulate NEC = constant
- Hence $$NEC = \frac{P}{NEP} = \frac{P \cdot \frac{\partial S}{\partial P}}{N} = \text{constant}$$
- Will impose a relation for S(P), via $t_{int}(P)$ or $C_{eff}(P)$
- This relation depends on N or N(P)

Note: $S == V_{signal}$, $N == V_{noise}$

keep NEC constant by varying t_{int} or C_{eff} during integration

Nature of noise N

Noise sources that persist after calibration in high end imagers

	t_{int} varies	C_{eff} varies
	$NEC = \dfrac{SR \cdot \left(\dfrac{t_{int} . P}{C_{eff}} + \dfrac{\frac{\partial t_{int}}{\partial P} \cdot P^2}{C_{eff}} \right)}{N}$	$NEC = \dfrac{SR \cdot \left(\dfrac{t_{int} \cdot P}{C_{eff}} + \dfrac{t_{int} \cdot P^2 \cdot \frac{-\partial C_{eff}}{\partial P}}{C_{eff}^{\ 2}} \right)}{N}$
	$NEC = \dfrac{Q_{photo} \cdot \frac{\partial Q_{signal}}{\partial Q_{photo}}}{Q_{noise}}$	$NEC = \dfrac{Q_{photo}}{Q_{noise}}$

Nature of noise N	Noise source	t_{int} varies	C_{eff} varies
Constant $charge_{RMS}$	kTC noise	**t_{int}~1/Q**	C_{eff}~Q^2
Constant $voltage_{RMS}$	EMI, read noise, ADC...	**t_{int}~1/Q**	**C_{eff}~Q**
~√power	PSN	**t_{int}~1/Q**	No solution
~√t_{int}	DCSN	t_{int}~$1/Q^2$	No solution
~power	PRNU	Always fulfilled	Always fulfilled
~t_{int}	DSNU	No solution	No solution

Ref. B. Dierickx, "Wide dynamic range: the pixel's standpoint", ISSCC 2008

Interpretation

The relations t_{int}~1/Q and C_{eff}~Q found are essentially "logarithmic responses"

$$V_{signal} = \frac{1}{t_{\text{int max}}} \cdot \int_0^{Q_{photo}} \frac{t_{\text{int}}(Q)}{C_{eff}(Q)} dQ \sim \int_0^{Q_{photo}} \frac{1}{Q} dQ$$

$$V_{signal} \sim \log_n(Q_{photo}) + Cte$$

Is a consequence of imposing a constant NEC

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Examples of AC information

- Extract a modulated light source from a DC background
  - E.g. recognize an IR remote control or an IR transmitter in a scene
  - Artificial light source flicker detection
- Time of flight
  - Ranging: sample and time stamp the light returning from an illuminator
- Time gating
  - Acquire light only during precise fractional time spans
  - Acquire only light from a certain distance – as reflected from a short illuminator pulse – or signals at very precise moments – or an accurate global shutter.

Extract AC from DC

- How to extract AC information from a huge dynamic range scene

⇒Brute force: acquire multiple DC frames, and demodulate off line

Sensor must handle full DR; and many frames
Uncorrelated noise accumulates

⇒More subtle: Subtract DC part from the signal, acquire the AC part only and demodulate off-line or in electrical domain

Sensor must only handle AC
Uncorrelated noise accumulates

⇒Best: demodulate in optical or charge domain and acquire that image

Sensor must only handle AC
No uncorrelated noise

Image sensor detection chain

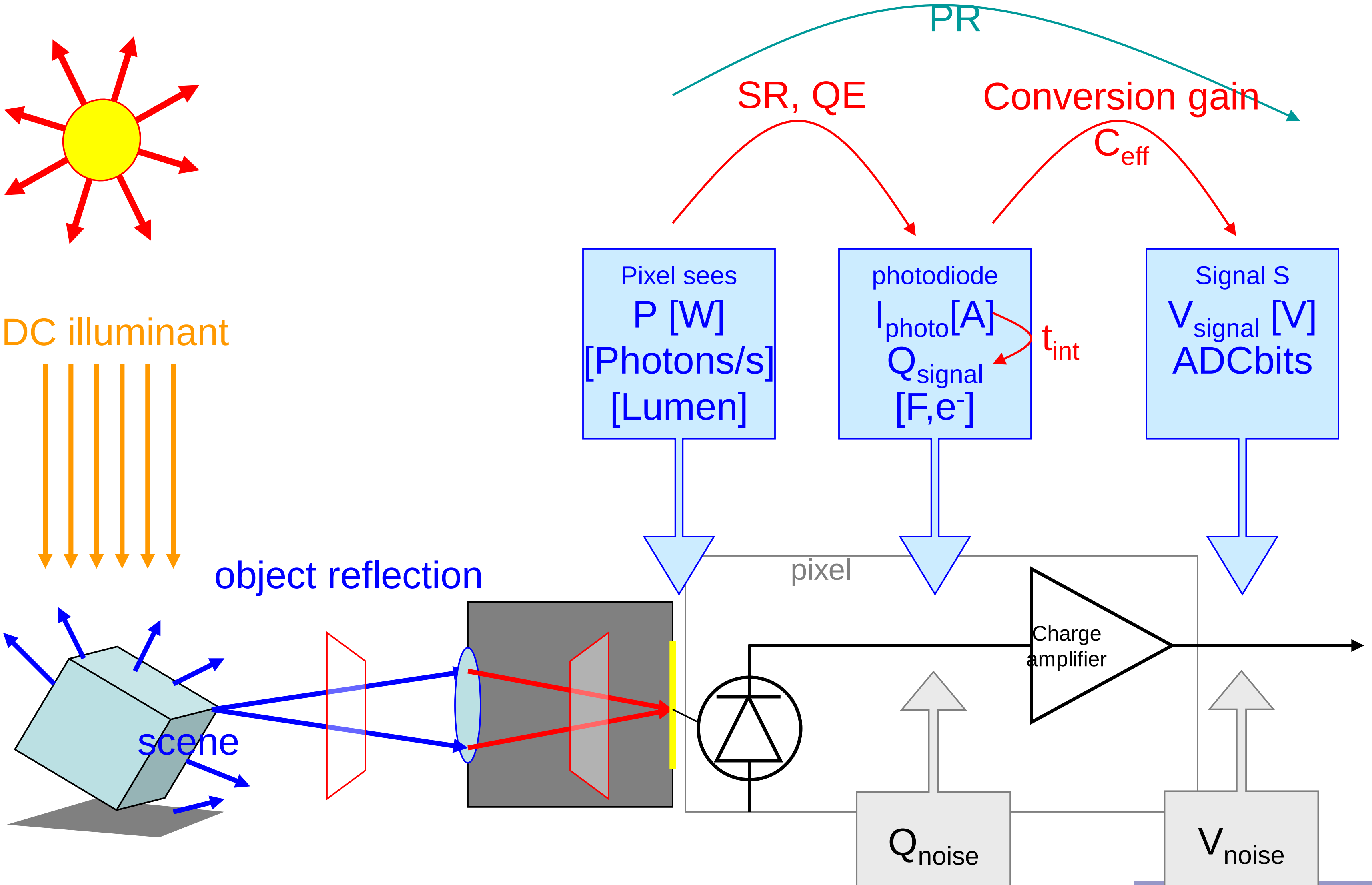


Image sensor detection chain

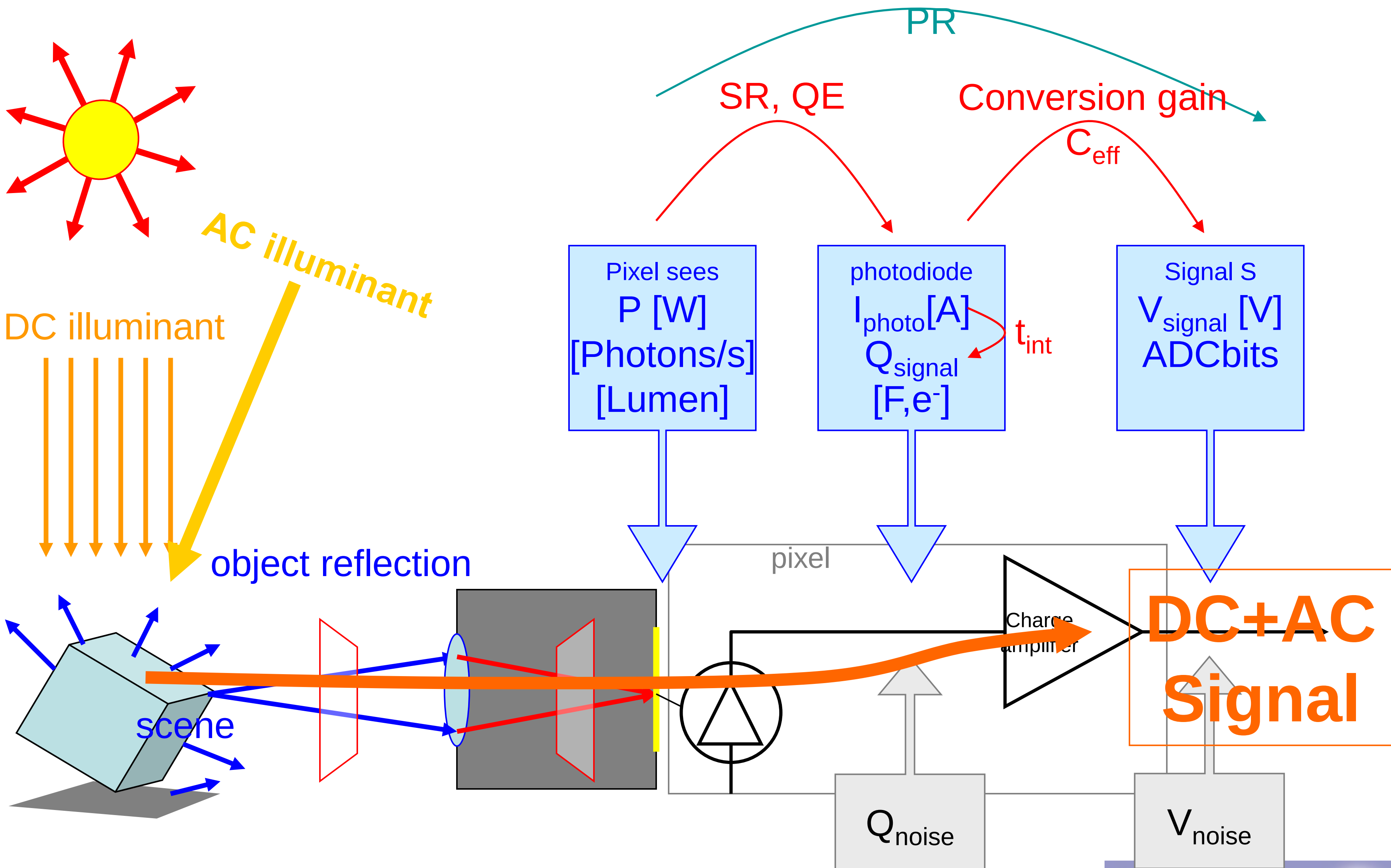
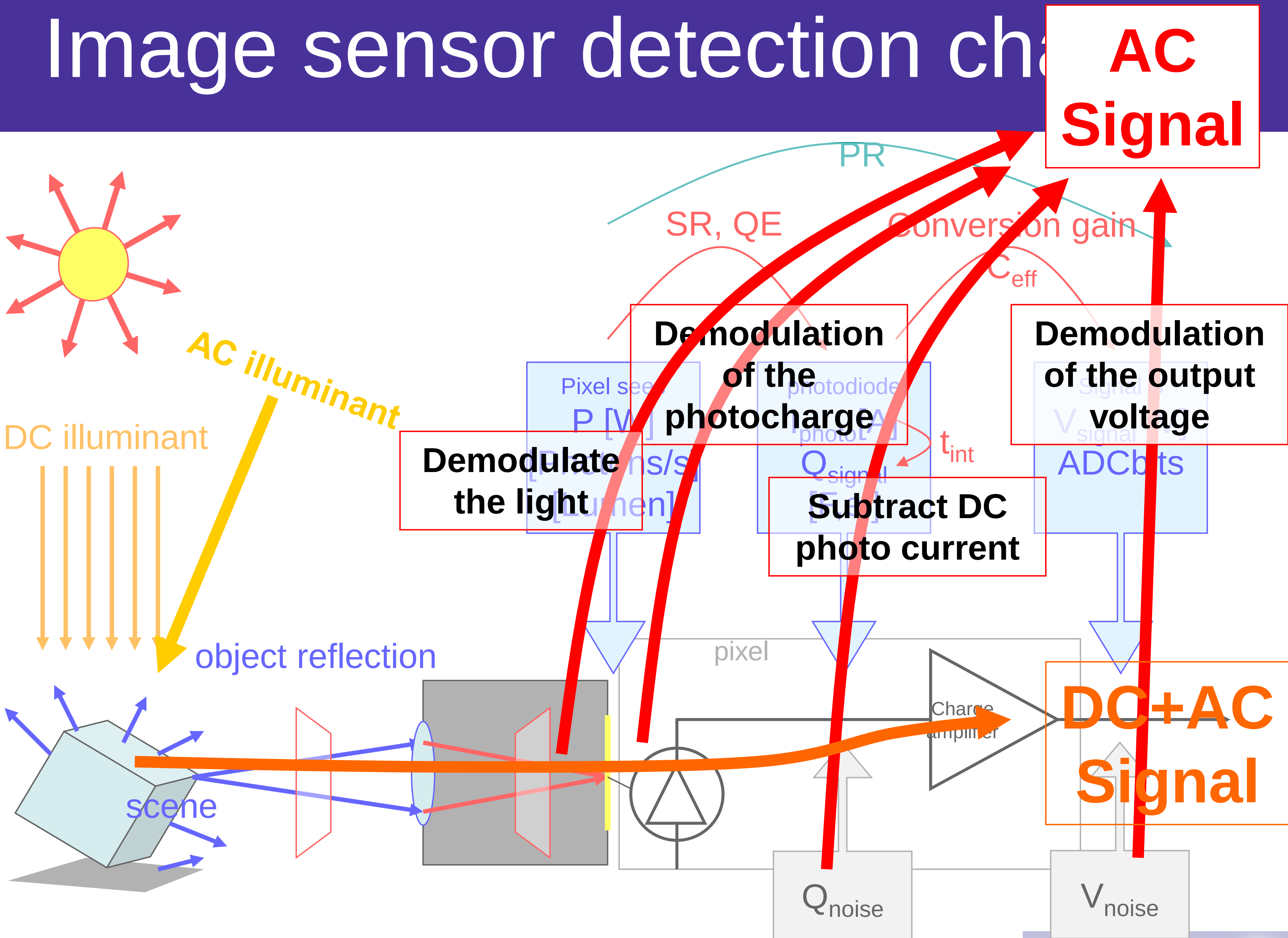
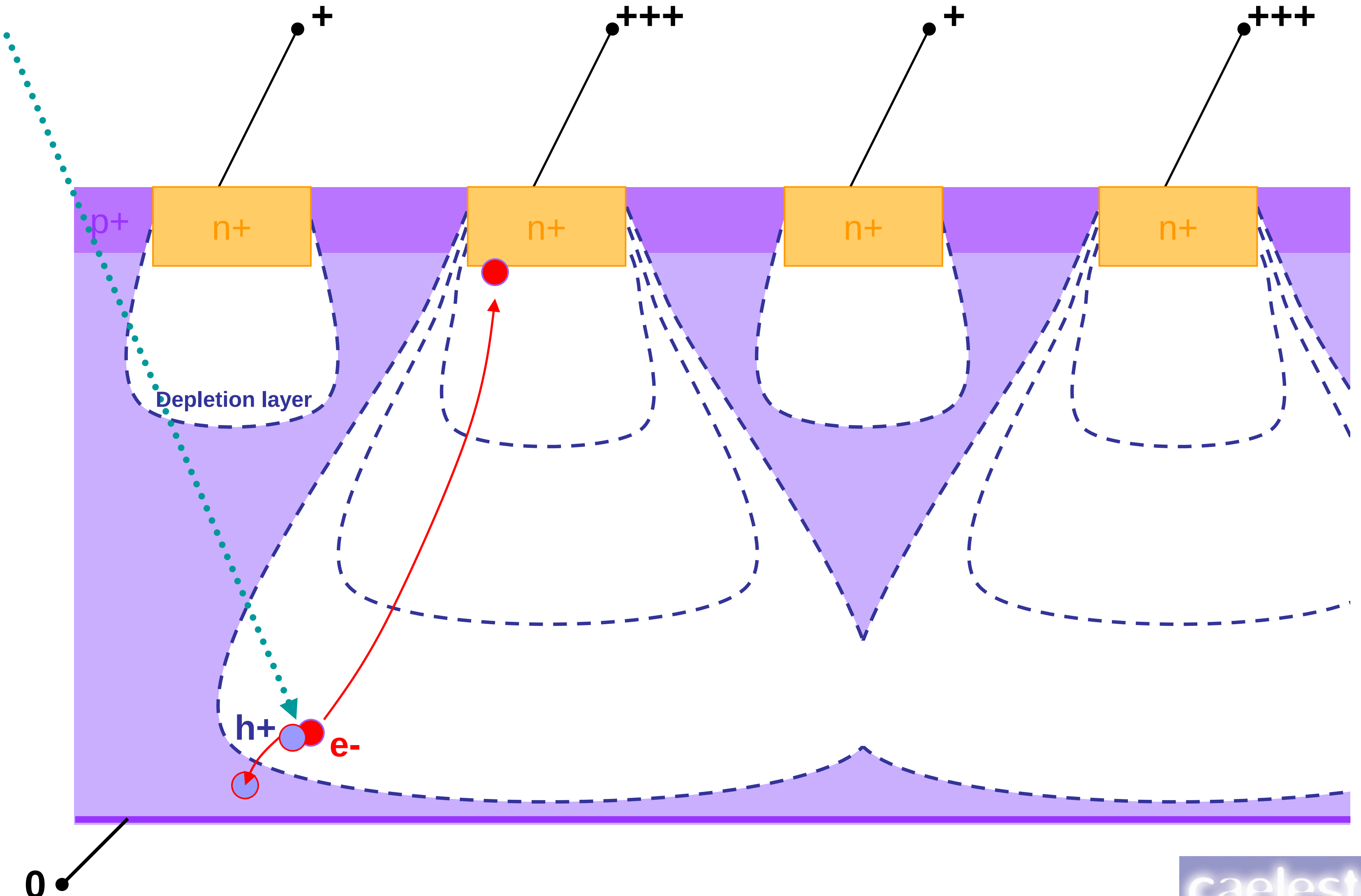


Image sensor detection cha



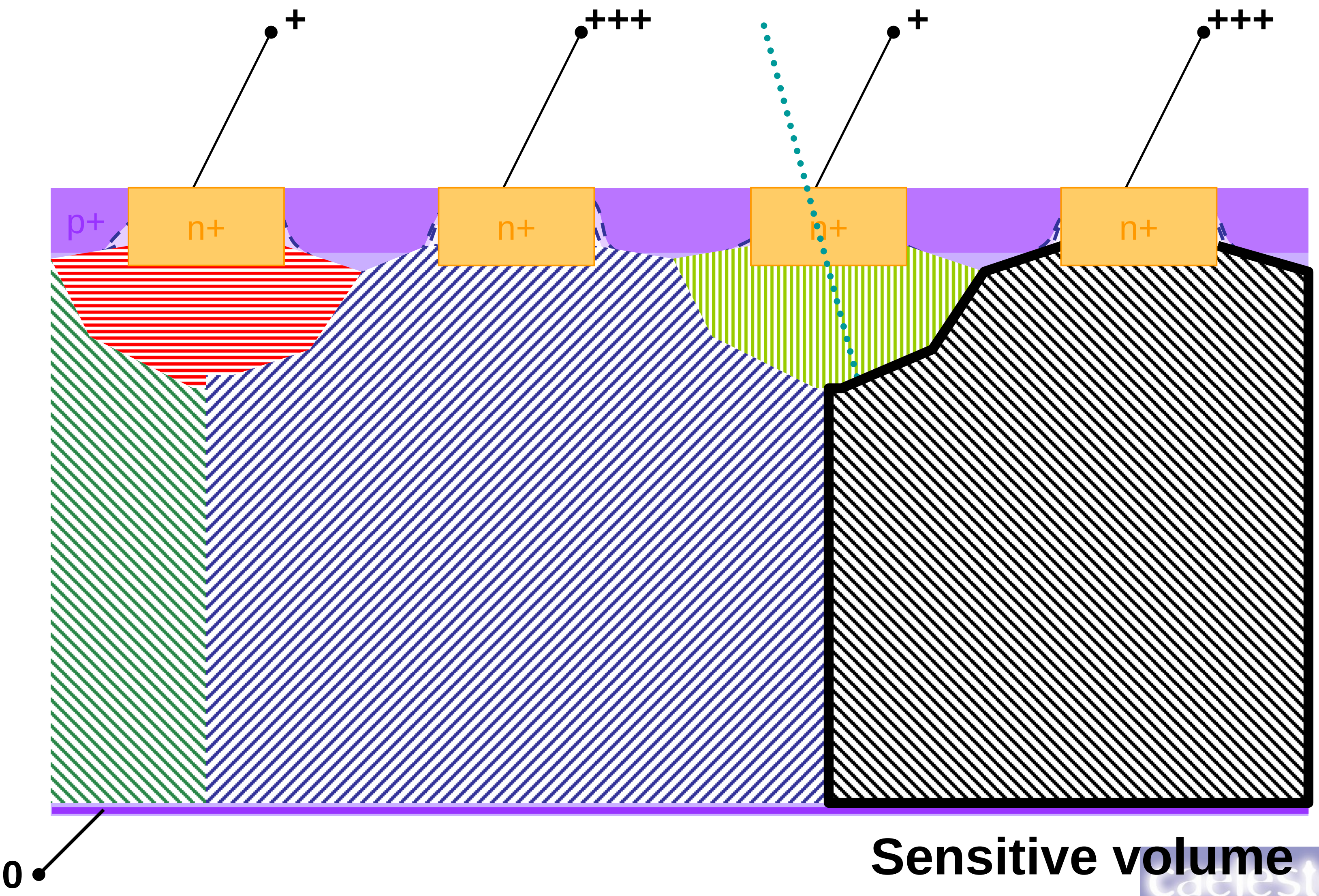
time gating pixel
demodulating in charge domain

Continuously tunable sensitive volume

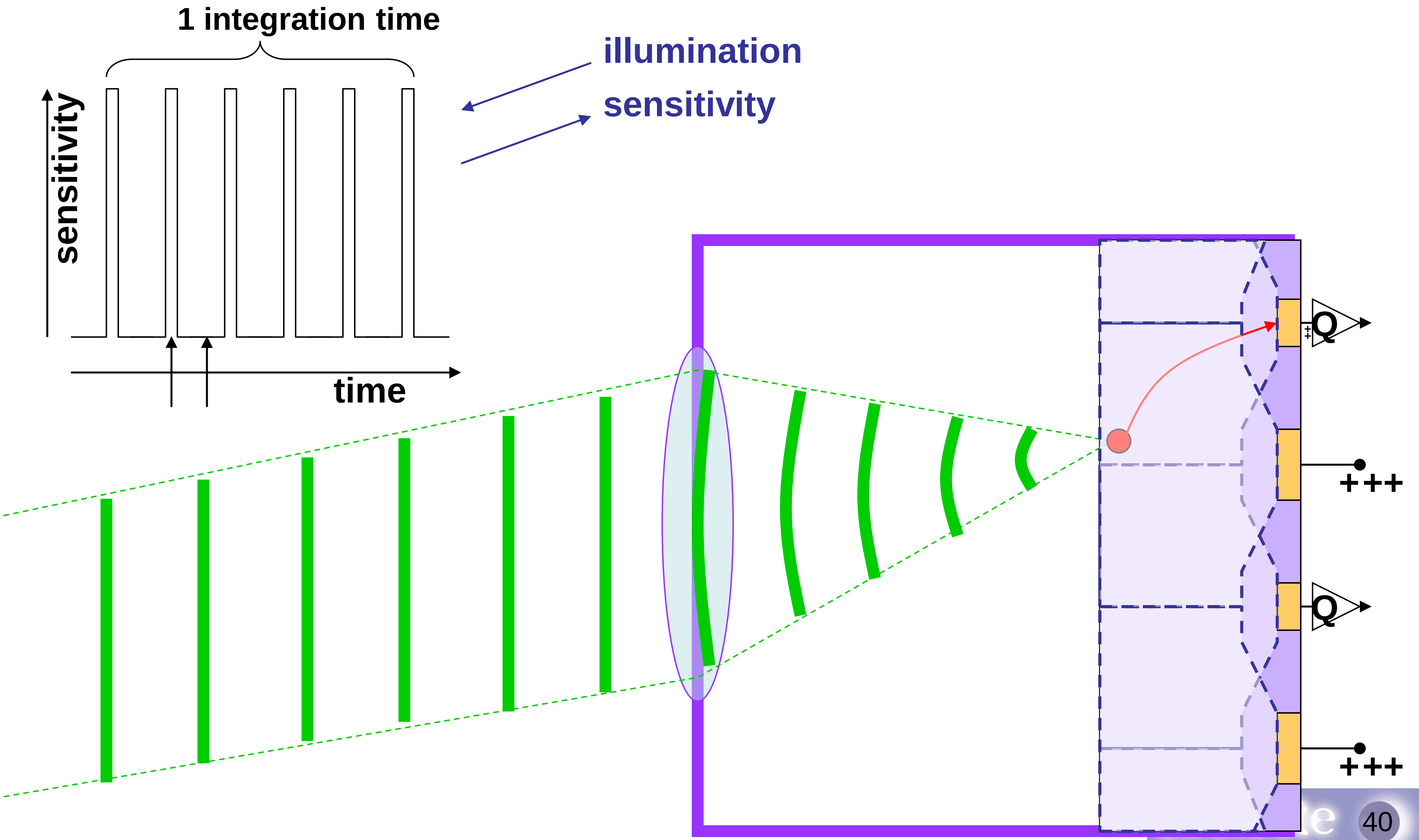


Continuously tunable sensitive volume

Patent pending



Time gating


1 integration time
sensitivity
time
illumination
sensitivity
Q
+++
Q
+++

Preliminary device specs

Geometrical

- Array: 360x720 pixels
- 30 fps nominal
- Pixel pitch 20 µm
- Technology: 0.35um CMOS
- Substrate: backside thinned, 5E12/cm^3 p-type
- Gating / switching speed: <<1ns effective
- Gating on/off cycle: >100kHz

Electro-optical

- Full well 50000 e-
- Read noise: 20e- (below kTC) per pixel/frame
- QE > 80% visible range
- *PS*(λ) Parasitic sensitivity when gate is off < 1% in BSI
- DC/AC suppression factor: minimum of PS and duty cycle.
- Shortest global shutter time < 1 ns

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Worth remembering

- *High dynamic range* is a property of the scene and light source.
  - The sensor has to accommodate.
- DC: When you want to acquire the “scene”:
  - One must apply some form of non-linear response
  - ⇨ have a sufficient NEC in all parts of the image/scene
- AC: When you want to extract AC information from the large DC background:
  - Demodulate as early as possible: in optical or charge domain, better than in voltage domain or off-line
  - ⇨ have as high as possible NEC for the AC signal only